NUCLEAR SAFETY

D. BUDEN

Nuclear safety concerns can be thought of in terms of terrestrial, unmanned space operations, manned space operations, and Moon and planetary bodies. These are overlapping in many respects; however, there are unique aspects associated with each area (Figure 1). For instance, for terrestrial operations, one must be concerned with the anti-nuclear bias and the strict laws that must be adhered to in order to protect the environment and people. For unmanned space operations, the main concerns are related to low orbits and final disposal. Manned operations add a new class of problems concerning the safety of the crew. For instance, if a nuclear propulsion unit fails on the way to Mars and the crew keeps going with no way to get home, this is not acceptable. Surface power supplies have their own unique features, but these are a subject for a different meeting.

When one discusses safety of nuclear power and propulsion, one observes overlapping and unique areas (Figure 2). Nuclear propulsion rockets have to deal with hydrogen exhausting out of a nozzle that could contain fission products or radioactive materials. Nuclear power systems need to be concerned with high burn up and fission products and actinides formed over long operating times.

It is highly desirable to have a set of generic space safety guidelines. However, such guidelines do not exist. One document on safety issued in the 1970's, OSNP-1, includes an overall safety philosophy that pretty well summarizes the U.S. safety philosophy. It states that the policy of the United States for all U.S. nuclear power sources in space is to ensure that the probability of release of radioactive material and the amounts released are such that an undue risk is not presented, considering the benefits of the mission (Figure 3). Each program, such as SP-100, includes its own version of safety requirements as part of the specifications.

General safety design requirements are given in Figure 4. In case of an accident, the reactor must be maintained subcritical if it is immersed in water or other fluids. Essentially, this relates to launch pad abort situations. Next, the reactor needs to have a significant effective negative power coefficient--unfortunately, what is meant by significant is not well defined. No credible launch accident may cause criticality relating to fires and explosions that could result in a critical reactor generating significant amounts of radiation. The reason for no reactor operation until a stable flight path is achieved is for ground personnel safety and safety during launch aborts. The reactor radiation levels are very low prior to normally planned operation in space. Flight qualification will probably include a zero power test to check the nuclear physics of the reactor, but the radiation levels will still be sufficiently low to avoid the need for special procedures around the reactor on the launch pad. Two independent shutdown systems

will ensure that the reactor will shutdown when commanded. Independent decay heat removal paths are to avoid core meltdowns in case of a failure in the normal coolant path.

One important factor in preparing safety requirements is that each requirement should have an identifiable contribution to reducing safety related risk. The requirements should be generic and not specify design solutions. In other words, safety requirements should address safety issues and not particular design concepts.

Undue risk is another concern in arriving at safety requirements. There is no legal definition for this term. For some, one in a million would be considered an acceptable definition. Others would argue for some other number. Obviously, the consequences of an event enter into what we accept as undue risk. The fact that we can not quantitize the definition makes it difficult for many engineers in system design .

Terrestrial safety factors are given in Figure 5. Testing nuclear electric propulsion power plants will require at least three independent barriers to radioactive materials being released to the biosphere. Also, there will need to be an independent decay heat removal system in case the primary coolant loop fails. Additional safety controls and instrumentation will be needed to monitor ground test operations.

SP-100 flight system requirements are given in Figure 6. These are part of the SP-100 requirements document. However, the document tends to include design solutions as part of the specifications. Generic safety specifications are preferable. SP-100 provides a starting point for nuclear electric propulsion safety specifications preparation.

For manned systems (Figure 7), the safest response to an abnormal event may not be to shutdown. If a habitat power system going to or on Mars is shutdown, the crew could lose their life support equipment--not a very safe approach. We are going to have to think about how to continue operations, even at a somewhat reduced level. Reactor scram at times is an unacceptable safety action.

From past programs, we can look at lessons learned (Figure 8). Safety must start with the initiation of the design process! A systematic determination of the effects of all possible failures is needed right at the beginning of the design process. Countermeasures must be developed for significant accident situations. The cost and benefits of mitigation need to be assessed and appropriate remedies applied. Safety must be given more then lip service and must truly be given primary priority.

SP-100 has recently performed detailed safety studies through all phases: ground operations, launch, flight and disposal (Figures 9 and 10). The issues are similar to those that will need to be addressed in nuclear electric propulsion power plants. This has led to many design features (Figure 11 and 12), such as two independent shutdown systems, control rods in the core, a special in-core method of cooling the system in case primary

coolant is lost, and a reentry cone around the reactor.

During ground operations (Figure 13), the key concerns are to prevent accidental criticality, avoid loss of special nuclear materials to terrorists, and ensure that radiation levels around the launch pad are sufficiently low to ensure that special precautions are not necessary for worker safety. The approaches for accomplishing safety, as given on the figure, are well known.

For launch operations (Figure 14), the key concerns are to prevent accidental nuclear criticality and to keep foreign countries from acquiring special nuclear material. For instance, if an abort occurred during launch operations, we do not want special nuclear material ending up in a foreign country and starting an international incident. Approaches exist as to how to address these concerns. Redundant neutron poisons can take care of preventing accidental criticality. In the NERVA program, we not only had the control drums, but also had wires in the core that would be extracted when the nuclear stage was separated. This provided independent redundant safety systems.

To ensure that an abort would lead to nuclear material being dispersed over water, on-board destruct devices are used. Early launch aborts will end up in the Atlantic Ocean. Later aborts have sufficient momentum to carry the satellite over an ocean where the destruct device can destroy the satellite.

In flight operations (Figure 15), the key concerns have to do with unplanned reentry into the biosphere and crew safety. Unplanned reentry can be reduced to very low probability levels by selecting the flight trajectory to always move towards a safer orbit. Interlocks can be used to shutdown the reactor if an unsafe condition is sensed. For crew safety, either redundant systems need to be supplied or means to continue to operate to bring the crew home. One must decide how much redundancy in engines and power plants are going to be required to get home safely. One concept is to use seven engines with a two engine out capability. This changes the thrust level and design complexity of the engine and drives the whole development program. This issue is important to resolve at the beginning of the systems engineering process.

Final disposal (Figure 16) must be considered to avoid reentry of the reactor into the biosphere or contamination of low Earth orbit. The approach is to avoid bringing it back to low Earth orbit when feasible and to select orbits to minimize risk. Returning from Mars, a nuclear thermal rocket can be disposed of in deep space with final capture of the crew capsule by aerocapture. This way, the nuclear thermal rocket can be disposed of so that it never passes in the vicinity of the Earth.

Perceived safety (Figures 17 and 18) is an interesting subject because the public's perception of safety is not the same as actual safety. Figure 17 shows the real safety of SP-100. It is significantly safer then a transcontinental aircraft flight, diagnostic medical services, radiation therapy or lifetime natural environments. As experienced in the

nuclear industry, the real and perceived safety are often very different. The nuclear industry probably has the safest record of any major industry in this country, but if you ask the average person on the street, he probably thinks it is more dangerous than driving a car. Perceived safety is an emotional issue and emotional issues are hard to deal with. However, this is something that has to be addressed early in the program. Reducing the real risk to a very low level helps in reducing perceived safety risk.

Turning to licensing, the users must know that launch approval will be granted in a timely fashion (Figures 19 and 20). A procedure is in place to accomplish this. The Interagency Nuclear Safety Review Panel performs independent safety/risk evaluations, the agency flying a payload requests permission for flight, the Office of Science and Technology Policy (OSTP) reviews the request and makes the launch decision, the Executive Office of the President makes the final decision if OSTP feels that it is appropriate.

The NERVA program design philosophy is given in Figure 21. Safety was a driving force in the flight engine design. The NERVA flight engine program and safety plan are summarized in Figures 22 and 23. They included detailed safety analyses and experiments and a requirement to be able to continuously provide 30,000 lb thrust in an emergency mode.

In summary, potential solutions exist to reduce risk to acceptable levels. Unless safety is considered from design selection and initiation, the cost of safety goes up dramatically. Not only must the safety risk be reduced to acceptable levels, it must be done in a manner that the perceived risk to the decision makers and public is acceptably low. Licensing procedures are in place and the duration of the licensing process is predictable. Users can count on approval for launch if procedures are followed and operational constraints are similar to chemical systems.

BIBLIOGRAPHY

David Buden
Nuclear Safety

1. Buden, D. and Joseph Angelo, Jr. *Space Nuclear Power,* Orbit Series, Melbourne, Florida, Krieger, 1985.

2. -----. "The Broad View of Nuclear Technology for Aerospace," 8th Symposium on Space Nuclear Power System, January, 1991.

3. Lee, J., et. al., 1990. "Technology Requirements for the Disposal of Space Nuclear Power Sources and Implications for Space Debris Management," AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, AIAA 90-1368, Baltimore, Maryland, April 18, 1990.

4. Buden, D., 1989. "Mars Mission Safety," *Aerospace America,* June 1989, pp. 22-25.

5. Buden, D., 1988. "Review of Nuclear Rocket Safety Program," NASA Nuclear Thermal Rocket Propulsion Workshop, Cleveland, Ohio, August, 1988.

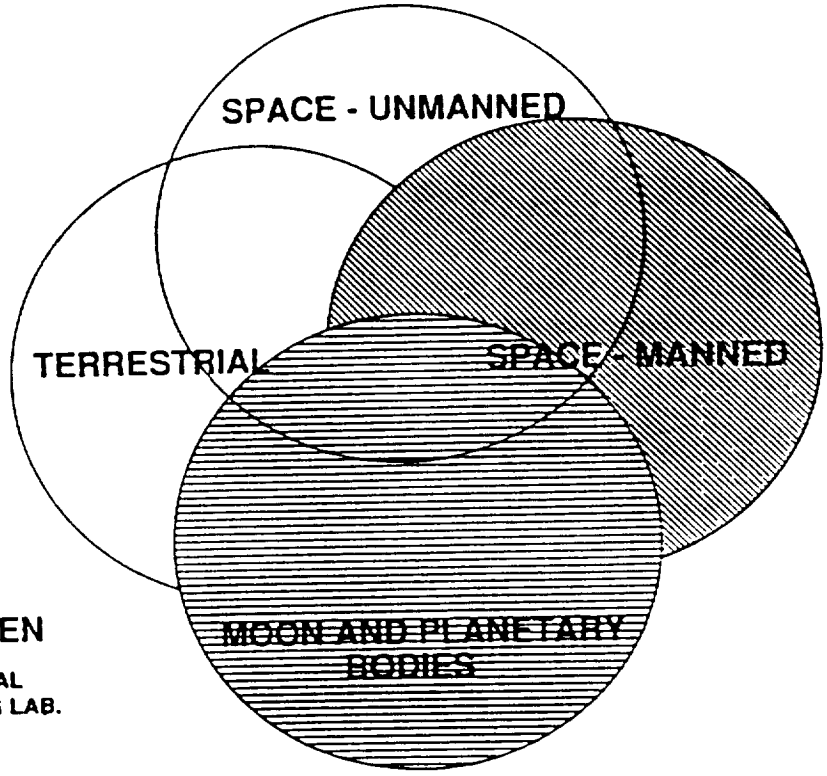
6. Buden, D., 1987. "Nculear Rocket Safety," 38th International Astronautical Congress of the IAF, Brighton, United Kingdom, October, 1987, Paper No. IAF-87-297, Volume 18 of Acta Astronautica.

7. Angelo, J., Jr., and D. Buden, 1987. "Space Nuclear Reactors - A Post=Operational Disposal Strategy," 38th International Astronautical Congress of the IAF, Brighton, United Kingdom, October, 1987, Paper No. IAF-87-237, Volume 18 of Acta Astronautica.

8. Buden, D., 1987. "Flight Safety Lessons from NERVA," 22nd Proceedings of the Intersociety Energy Conversion Engineering Society, Phildelphia, Pennsylvania, August, 1987, pp. 457-461.

9. Buden, D., 1987. "Safety Constraints and Considerations in Development of Nuclear Powered Propulsion," 4th Symposium on Space Nuclear Power Systems, University of New Mexico, January 12, 1987, *Space Nuclear Power Systems 1987,* Orbit Book Company, Malabar, Florida, 1988, pp. 483-488.

SAFETY



DAVID BUDEN
IDAHO NATIONAL ENGINEERING LAB.
208-526-9881

Figure 1

SAFETY

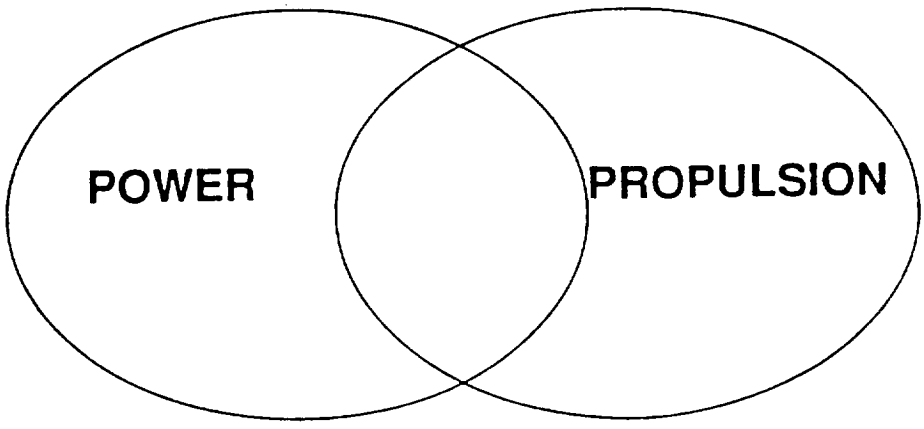


Figure 2

GENERAL SAFETY REQUIREMENTS

THE POLICY OF THE UNITED STATES FOR ALL U.S. NUCLEAR POWER SOURCES IN SPACE IS TO ENSURE THAT THE PROBABILITY OF RELEASE OF RADIOACTIVE MATERIAL AND THE AMOUNTS RELEASED ARE SUCH THAT AN UNDUE RISK IS NOT PRESENTED, CONSIDERING THE BENEFITS OF THE MISSION.

OSNP-1

Figure 3

SAFETY DESIGN REQUIREMENTS

- REACTOR DESIGNED TO REMAIN SUBCRITICAL IF IMMERSED IN WATER OR OTHER FLUIDS
- SIGNIFICANT EFFECTIVE NEGATIVE POWER COEFFICIENT OF REACTIVITY INCLUDED
- NO CREDIBLE LAUNCH ACCIDENT CAUSES CRTICALITY
- NO REACTOR OPERATION UNTIL STABLE FLIGHT PATH ACHIEVED
- TWO INDEPENDENT SHUTDOWN SYSTEMS
- INDEPENDENT DECAY HEAT REMOVAL PATH
- UNIRRADIATED FUEL POSE NO SIGNIFICANT ENVIRONMENTAL HAZARD

Figure 4

TERRESTRIAL SAFETY

- NUCLEAR ELECTRIC PROPULSION POWER PLANTS
  - THREE INDEPENDENT BARRIERS TO RADIOACTIVE MATERIAL RELEASE
  - INDEPENDENT DECAY HEAT REMOVAL SYSTEM
  - ADDITIONAL SAFETY CONTROLS AND INSTRUMENTATION
- NUCLEAR THERMAL ROCKETS
  - LOSS-OF-COOLANT FLOW SYSTEM
  - SCRUBBERS TO CLEAN EXHAUST OF RADIOACTIVE MATERIALS
  - CONTAINMENT/CONFINEMENT UNCERTAIN
  - ADDITIONAL SAFETY CONTROLS AND INSTRUMENTATION

Figure 5

SP-100 FLIGHT SYSTEM KEY SAFETY REQUIREMENTS

- MAINTAIN REACTOR SUBCRITICAL DURING ACCIDENTS AND DURING PERMANENT DISPOSAL
  - FUEL/SAFETY ROD ALIGNMENT
  - LAUNCH PAD FIRES
  - EXPLOSIONS
  - CORE IMPACTION
- INTACT REENTRY FOR SPECIFIED INADVERTENT EVENTS
- ESSENTIALLY INTACT BURIAL FOLLOWING INADVERTENT REENTRY
- HIGH RELIABILITY FOR REACTOR SHUTDOWN
- HIGH RELIABILITY FOR SHUTDOWN HEAT REMOVAL
- RETENTION OF REACTOR STRUCTURAL INTEGRITY FOR LOSS-OF-COOLANT
- SECURE COMMUNICATIONS AND INHIBITS TO PREVENT REACTOR STARTUP PRIOR TO OPERATIONAL ORBIT
- MINIMIUM USE OF HAZARDS, CHEMICALLY TOXIC MATERIALS

ARE THE REQUIREMENTS THE SAME FOR NEP POWER PLANTS?

Figure 6

SPACE--MANNED

- CONTINUING TO OPERATE MAY BE SAFER THAN SHUTTING DOWN
- MONITORING ASSESSMENT INSTRUMENTATION

Figure 7

SAFETY APPROACH

- SYSTEMATICALLY DETERMINE THE EFFECTS OF ALL POSSIBLE FAILURES
- ADVISE COUNTERMEASURES TO PREVENT A NUCLEAR ACCIDENT
- ACCESS THE COST AND BENEFITS OF MITIGATION
- RECOMMEND APPROPRIATE REMEDIES

MUST START WITH INITIATION OF THE DESIGN PROCESS!

Figure 8

POTENTIAL MISSION ACCIDENTS AND HAZARDS

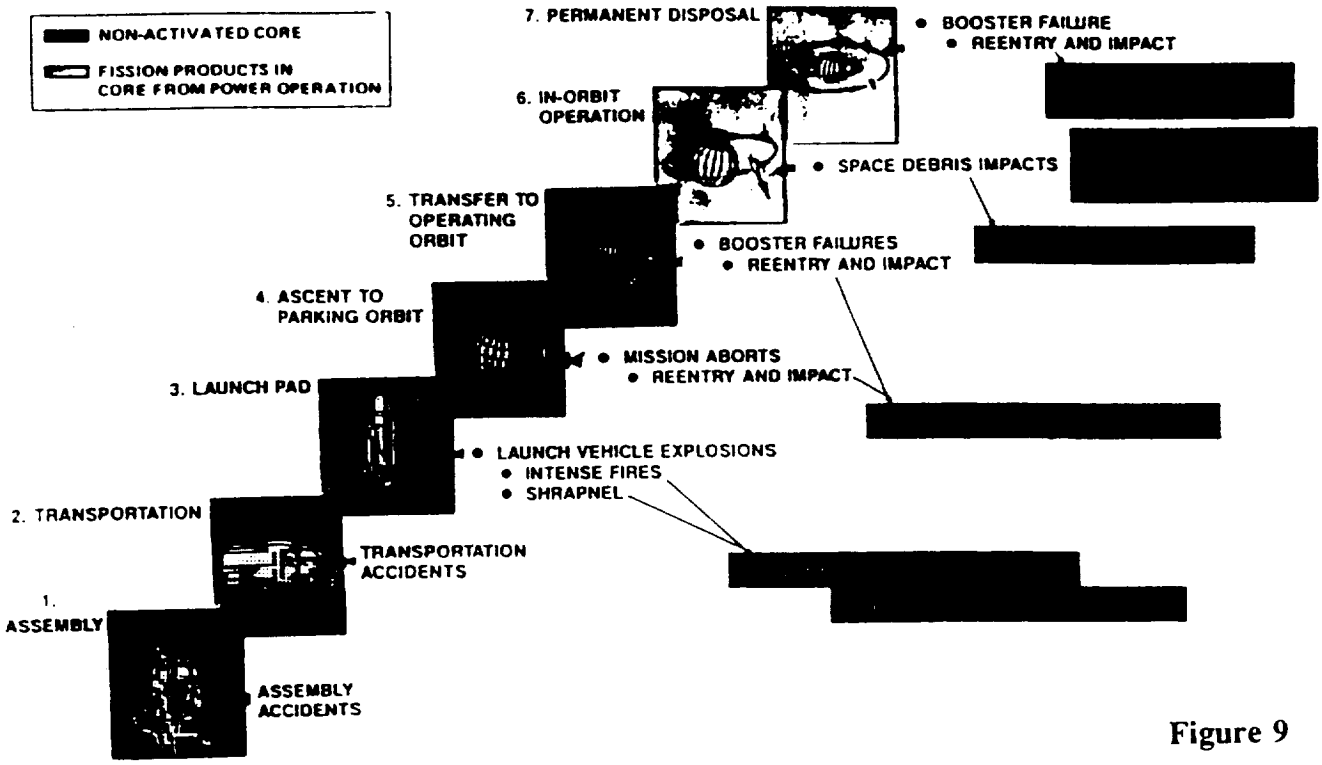


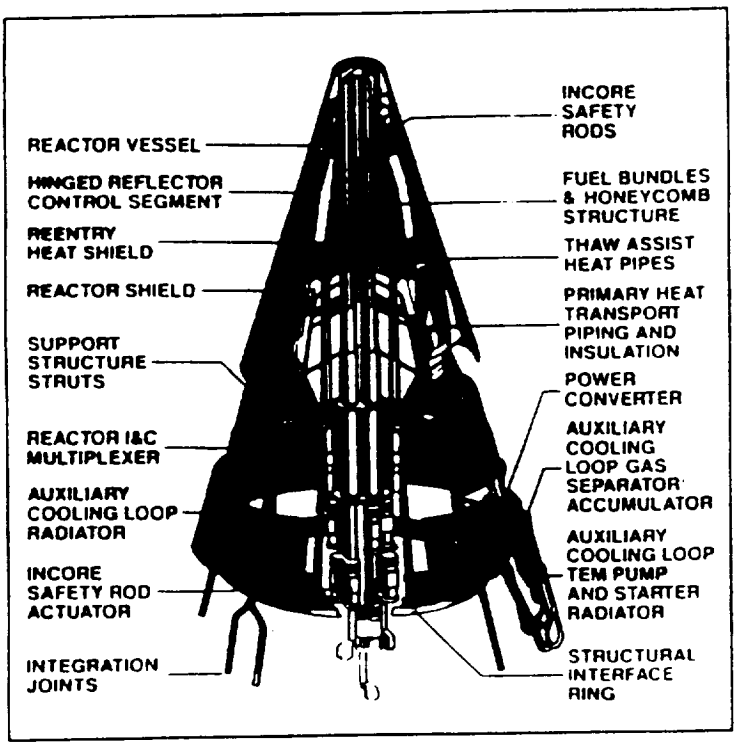
Figure 9

SAFETY CONCERNS

- GROUND
- LAUNCH
- FLIGHT
- DISPOSAL
- PERCEIVED
- LICENSING

Figure 10

KEY SAFETY FEATURES



- Control elements automatically shut reactor down upon loss of power
- Two independent shutdown systems
- Prompt negative reactivity coefficient assures stable reactor control
- Only 4 out of 12 reflectors required for shutdown
- Fresh core at launch
- Large negative void coefficient enhances shutdown upon loss of coolant
- Control elements moved individually and in icremental amounts to prevent rapid reactivity addition
- Rhenium poison provides thermal neutron absorption for water flooding

Figure 11

KEY SAFETY FEATURES (CONT.)

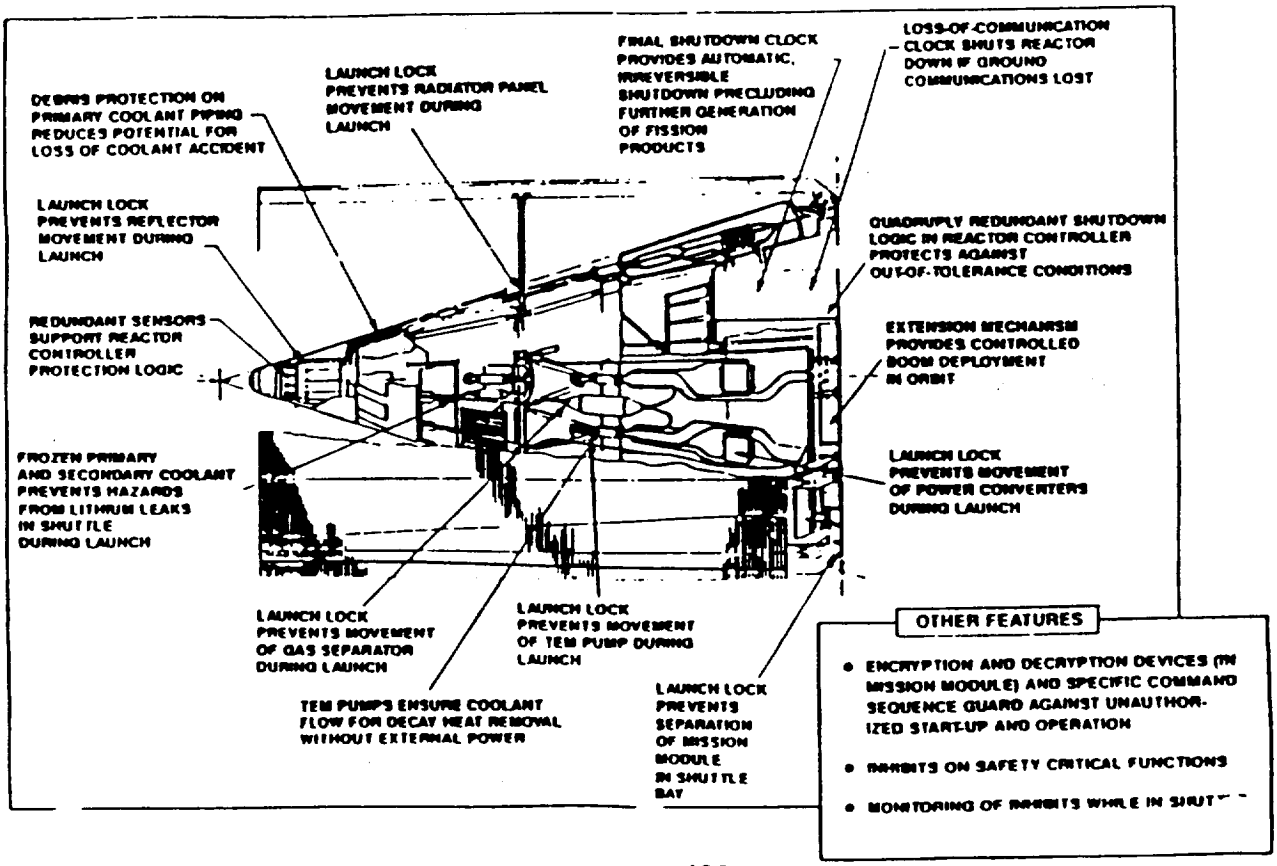


Figure 12

GROUND OPERATIONS

- KEY CONCERNS
  - PREVENT ACCIDENTAL CRITICALITY
  - AVOID LOSS OF SNM TO TERRORIST
  - WORKER CONSTRAINTS AROUND LAUNCH PAD
- APPROACHES
  - ENGINE TRANSPORT
    - CORE HEAVILY POISONED
    - WATER-TIGHT STRUCTURE
    - SHIPPING VESSEL FOR "WORST" IMPACT ACCIDENT
    - SHIPPED IN PREFERENTIAL MANNER
  - LAUNCH PAD OPERATIONS
    - KEEP RADIOACTIVE LEVELS BELOW SAFETY LIMITS
    - REDUNDANT AND INDEPENDENT NEUTRON POISONS (E.G., POISON RODS IN COOLANT CHANNELS, LOCKED DRUM SUBSYSTEM)

Figure 13

LAUNCH OPERATIONS

- KEY CONCERNS
  - PREVENT ACCIDENTAL CRITICALITY
  - AVOID FOREIGN COUNTRY ACQUIRING SNM
- APPROACHES
  - REDUNDANT AND INDEPENDENT NEUTRON POISONS
  - ON-BOARD DESTRUCT DEVICES
  - FLIGHT PATH IN PREDETERMINED ZONES

Figure 14

FLIGHT OPERATIONS

- KEY CONCERNS
  - UNPLANNED REENTRY INTO BIOSPHERE
  - RADIOLOGICAL EFFECTS ON CREW
  - FISSION PRODUCT RELEASE
  - CONTINUING OPERATIONS TO GET HOME
- APPROACHES
  - SELECT ANGLES OF THRUST TO ALWAYS MOVE TO SAFER ORBITS
    - SET ORBITS FOR SAFETY
    - INTERLOCKS
    - ENGINE DESTRUCT SYSTEM
  - REDUNDANT AND INDEPENDENT REACTOR CONTROL MODES (INCLUDING SET BACK MODES)
  - SHIELDING USING CONFIGURATION, LH2 IN TANK AND SPECIAL MATERIALS
  - ENCAPSULATED FUELS
  - REDUNDANT ENGINES/POWER PLANTS AND COMPONENTS

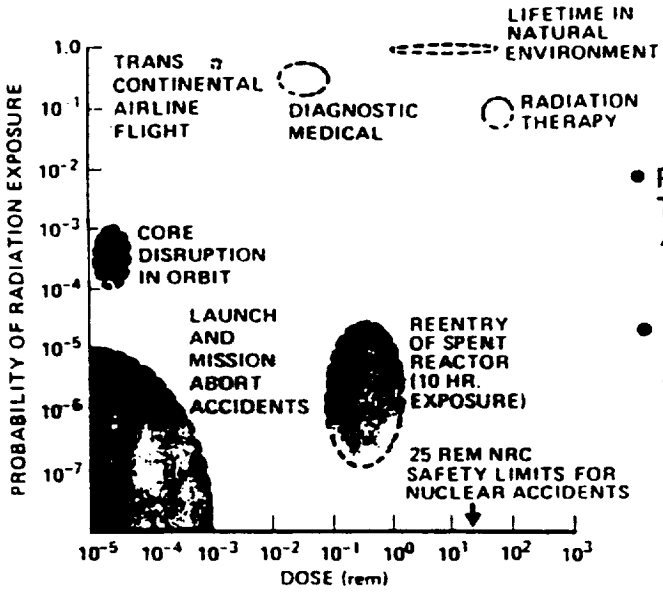
Figure 15

DISPOSAL

- KEY CONCERNS
  - REENTRY INTO THE BIOSPHERE
  - CONTAMINATION OF LOW EARTH ORBIT
- APPROACHES
  - DON'T BRING IT BACK TO LOW EARTH ORBIT
  - SELECT ORBITS TO MINIMIZE RISK

Figure 16

SP-100 RADIATION EXPOSURE vs. PROBABILITY



- PROBABILITIES OF SP-100 ACCIDENTS THAT RELEASE RADIOACTIVITY ARE LOW
- EVEN IF THE ACCIDENTS OCCUR, RADIATION EXPOSURES ARE WITHIN LIMITS

Figure 17

PERCEIVED SAFETY CONCERNS

- KEY CONCERNS
  - REAL AND PERCEIVED RISK CAN BE VERY DIFFERENT
  - EMOTIONAL ISSUE
- APPROACHES
  - REDUCE REAL RISK TO VERY LOW LEVEL
  - OPERATIONAL SCENARIOS MUST BE PLAUSIBLE AND COMPLETE (EX. DISPOSAL)
  - EDUCATION OF CONCERNED GROUPS
  - AVOID DISCUSSIONS OF PROBABILITIES (USE ANALOGIES)

Figure 18

LICENSING

- KEY CONCERN
  - TIMELY LAUNCH APPROVAL
- APPROACHES
  - CONSIDER SAFETY FROM THE START
  - WORK CLOSELY WITH IN PLACE APPROVAL PROCESS

Figure 19

SAFETY APPROVAL PROCESS

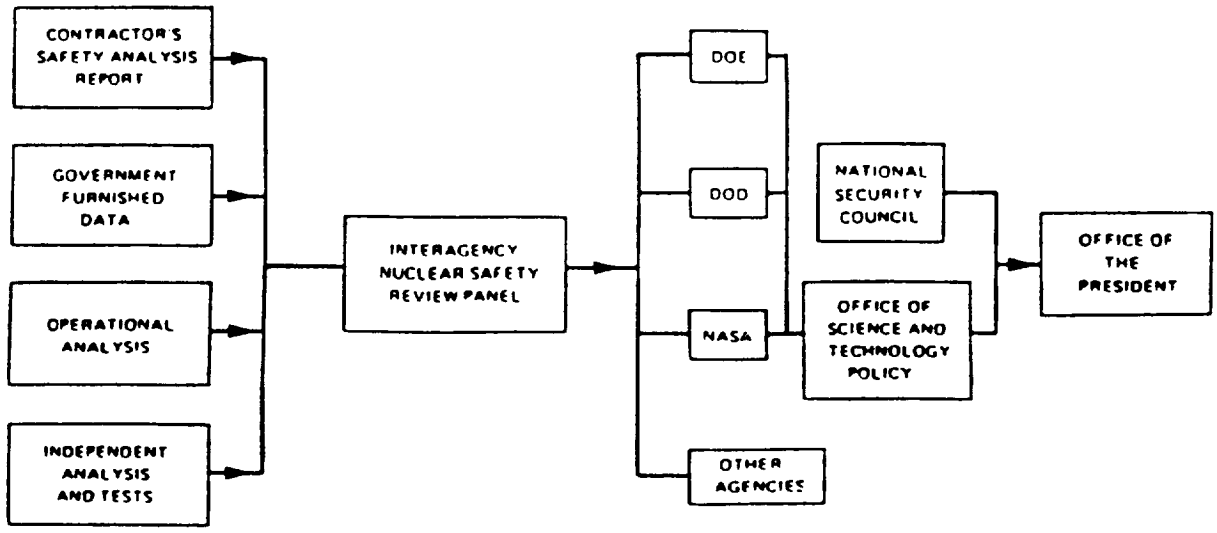


Figure 20

NERVA DESIGN PHILOSOPHY

"THE MAJOR DESIGN CRITERIA FOR THE NERVA ENGINE DEVELOPMENT PROGRAM SHALL BE RELIABILITY AND THE ACHIEVEMENT OF THE HIGHEST PROBABILITY OF MISSION SUCCESS. NEXT IN THE ORDER OF IMPORTANCE MUST BE PERFORMANCE AS MEASURED IN TERMS OF SPECIFIC IMPULSE. THEN THE ENGINE DESIGN SHOULD ATTEMPT TO KEEP THE OVERALL WEIGHT AS LOW AS POSSIBLE WITHIN THE BOUNDS ALLOWED BY FUNDS AVAILABLE FOR DEVELOPMENT. WHILE THERE ARE INTERRELATIONS BETWEEN THESE CRITERIA IN DESIGN, I CAN SEE NO BASIS FOR ALTERING THEIR ORDER OF IMPORTANCE."

MR. MILTON KLEIN (1967)

Figure 21

NERVA FLIGHT SAFETY PROGRAM

- SAFETY PLAN (S-019)
- FAULT TREE ANALYSIS PROCEDURES (S-019-002)
- FLIGHT SAFETY CONTINGENCY ANALYSIS REPORT (S-103)
- RELIABILITY ALLOCATION, ASSESSMENTS AND ANALYSIS REPORT (R202)
- SINGLE-FAILURE-POINT REPORTING, ANALYSIS, CORRECTION AND CLOSEOUT (R101 - NRP-306)

Figure 22

NERVA SAFETY PLAN

- THE MEANS FOR PREVENTING THE INADVERTENT ATTAINMENT OF REACTOR CRITICALITY THROUGH ANY CREDIBLE COMBINATION OF FAILAURES, MALFUNCTIONS, OR OPERATIONS DURING ALL GROUND, LAUNCH, FLIGHT, AND SPACE OPERATIONS.
- A DESTRUCT SYSTEM DURING LAUNCH AND ASCENT TO ASSURE SUFFICIENT DISPERSION OF THE REACTOR FULE UPON EARTH IMPACT TO PREVENT NUCLER CRITICALITY WITH THE FUEL FULLY IMMERSED IN WATER.
- THE MEANS FOR PREVENTING CREDIBLE CORE VAPORIZATION OR DISINTERGRATION OR VIOLATION OF THE THRUST-LOAD PATH TO THE PAYLOAD.
- DIAGNOSTIC INSTRUMENTATION ADEQUATE TO DETECT THE APPROACH OF A FAILURE OR AN EVENT THAT COULD INJURE THE CREW OR DAMAGE THE SPACECRAFT AND THE PROVISIONS TO PRECLUDE SUCH AN EVENT.
- THE CAPABILITY FOR REMOTE OVERRIDE OF THE ENGINE PROGRAMMER BY THE CREW AND GRUND CONTROL AS WELL AS FOR REMOTE SHUTDOWN INDEPENDENT OF THE ENGINE PROGRAM.
- AN ENGINE CONTROL SYSTEM CAPABILITY TO PRECLUDE EXCESSIVE OR DAMAGING DEVIATIONS FROM PROGRAMMED POWER AND RAMP RATES.
- PROVIDE AN EMERGENCY MODE ON THE ORDER OF 30,000 lb-thrust, 500s SPECIFIC IMPULSE AND 10^8 lb-sec TOTAL IMPULSE.

Figure 23

SUMMARY

- POTENTIAL SOLUTIONS EXIST TO REDUCE RISK TO ACCEPTABLE LEVELS
- THE COST OF SAFETY GOES UP DRAMATICALLY IF NOT CONSIDERED FROM DESIGN SELECTION AND INITIATION
- PERCEIVE SAFETY CONCERNS MUST BE ADDRESSED
- LICENSING PROCEDURES IN PLACE AND PREDICTABLE
- OPERATIONAL CONSTRAINTS ARE SIMILAR TO CHEMICAL SYSTEMS

Figure 24